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ADVISORY GROUP FOR AERONAUTICAL RESEARCH AND DEVELOPMENT

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THE DESIGN AND OPERATION OF MULTI-STAGE ROCKET VEHICLES

by

H. F. HALSTED

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NORTH ATLANTIC TREATY ORGANISATION

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SUMMARY

This paper reviews certain major interrelationships existing between the various branches of engineering concerned with the design and operation of unguided multi-stage rocket vehicle systems.

It is strongly emphasized that the attainment of a high degree of probability of success for the *first* flight is a relatively simple matter in some of the applied branches of engineering. The suggestion is made that throughout the entire project the overall approach is continually reviewed to ascertain the effect of each detail on the whole program, so that no single design feature, fabrication process or other concomitant may seriously affect the success of the mission.

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THE DESIGN AND OPERATION OF MULTI-STAGE ROCKET VEHICLES

H.F. Halsted*

1. INTRODUCTION

The discussion to be presented in this paper will not attempt to outline a detail approach, since any detail discussion would probably be valid in its entirety only as applicable to a specific vehicle system. Experience has shown, however, that specific approaches are devised primarily from generalities in the many interrelated branches of engineering that must always be considered in any specific approach to the design and operational concept of a given rocket vehicle system. It is the purpose of this paper to review certain major interrelationships not discussed by others at this meeting. It is the further purpose to strongly emphasize that the design and operation of most unguided multi-stage rocket vehicle systems, such that the *first* flight has a high degree of assurance for a successful vehicle mission, is a relatively simple and straightforward exercise in some of the applied branches of engineering.

There are two primary elements of a successful and economical multi-stage vehicle:

Identification of the major problem areas;

Essentially simultaneous solution of these problems.

The problem areas that experience and basic knowledge have shown to be of importance, in addition to the others discussed during this meeting, are as follows:-

Preliminary design

Stability

Structural design and loads

Separation systems

Effect of aerodynamic heating on structural design

Structural alignment

Ignition systems

Hardware finishes

Launchers

Logistics

Launching operations.

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The balance of this discussion will examine these problem areas in relation to *each other* and will very briefly review the general procedures leading to simultaneous solution of the problems. Some of the practical considerations that often dictate, or at least greatly influence, design and fabrication compromises will be discussed.

2. PRELIMINARY DESIGN

Probably the most important phase of any design problem is the very first sequence of preliminary investigations where the overall objectives that define the desired end result are first related to specific means of accomplishing the end result. If the problem is of large magnitude and very complex, this first phase may be referred to as 'systems analysis' or some other phrase in contemporary terminology that will indicate the problem is indeed formidable. It is important to recognize, however, that this first step, this early phase of effort in turning an objective into a reality, is really a familiar engineering approach. This phase of effort in most United States organizations is referred to as 'preliminary design' and, where related to problems involving multi-stage rocket systems, is accomplished by a small group of engineers, each of whom is qualified in one or more of the applicable branches of engineering and each of whom is, above all, extremely versatile in that he has a good working knowledge of all the branches involved.

For a multi-stage system, the preliminary design procedures followed are those engineering procedures used in any matching of ways and means against objectives. This procedure is one of iteration, in that a rough solution is first assumed, checked for objective performance, refined, rechecked against requirements, and subsequently refined to the degree desired. These steps are normally accomplished for as many configurations as appear to hold promise. Obviously, those solutions which, after a cursory check, appear to fall short of requirements are discarded. The steps involved are as follows:-

1. Study the specifications or statement of objectives to be achieved.

2. Select rocket motors on the basis of total impulse, size, and shape.

3. Prepare rough layout or sketch of vehicle configuration.

4. Make weight estimate, including allowances for motors, aerodynamic stabilizing surfaces, interstage connecting hardware, electrical wiring, payload, etc.

5. Prepare rough graphs of velocity and altitude versus time.

6. Make preliminary performance analysis, which may at this time be done by hand calculations involving the following:-

    (a) Estimate of average drag during burning and coasting, from Step 5 above. For short burning or coasting periods (a few seconds) use entire period. For long burning rockets or coasts, investigate in several increments.

    (b) Subtract drag from thrust available during burning and solve for increase in velocity.

(c) Add drag and gravity effect during coasting and solve for decrease in velocity.

(d) Estimate altitude gained for each burning and coasting period.

(e) Check velocities and altitudes against original assumptions.

7. Revise sketch, weight estimates, trajectory plots as required and repeat Step 6. It is well at this time to investigate the effect of varying coasting times in order to *approach* optimization. At this stage it is not generally worth the effort to attempt to completely optimize this variable - in fact, great detail effort in any particular phase is a waste of time, since the solution is based upon estimates which will certainly change as the design progresses. The secret of successful preliminary design is to continually move forward but to keep all phases in balance.

It will be appreciated that, in carrying out the preceding steps, the designer has considered, but not examined in detail, all of the more specific elements that have been discussed at this meeting. The objective of this phase is therefore to define, first the configuration to be proceeded with, and second, limiting definitions which will allow specific detail design to proceed to the final point without major change.

As the specific and detail design progresses, backed up by more detail analyses, it will be found that the well conceived preliminary design effort has fixed the direction, and in most instances the method, of achieving desired objectives, but has done so with considerable latitude allowed as far as specific detail design solutions are concerned. Following the preliminary design effort, the various branches of engineering in their specialized forms are employed. Since the preliminary design effort left considerable latitude in detail approaches, a potential hazard exists in that uncoordinated efforts in the separate areas of specialization may result in each specialist assuming that the latitude allowed was intended only for him. The aerodynamicist may conceive a highly optimized aerodynamic configuration, the structural designer might use all weight allowances to make his design job easier and the ignition and pyrotechnic specialist may find he has no place to run cabling except strapped to the exterior of the vehicle. Perhaps the interrelationship of the various branches of engineering specialization can best be illustrated by discussing some of the more important areas separately. This will be done in the following paragraphs, but it must be kept in mind that each area of specialization cannot, in practice, be considered separately; it can only be considered as one part of the development of the final design in close relation to the other areas of specialization and with all effort being expended toward the achievement of final objectives.

3. STABILITY

In proceeding let us first consider vehicle stability. Since the multi-stage rocket vehicle will spend its initial life in the atmosphere, aerodynamic stabilizing surfaces such as fins, or stabilizing flares will be required for the unguided and uncontrolled configurations. Fins, flares, or combinations thereof, provided in the

vehicle in order to stabilize it, are generally of significant magnitude in the total vehicle weight, so there is a twofold reason for early examination of aerodynamic stability. Classical methods for estimating the aerodynamic center of the various stages are assumed as known. Stability is investigated by comparing the position of the aerodynamic center and the center of gravity for each separate stage flown. The aerodynamic center, of course, moves as Mach number changes and the center of gravity moves as propellant is burned. It is usually adequate at this phase of the design to supply sufficient fin or flare area to yield approximately one caliber of static margin throughout the atmospheric portion of the flight. This figure is, of course, somewhat dependent upon the degree of confidence which may be placed on the aerodynamic center estimate. In a hypersonic régime with a configuration not very amenable to estimating, the static margin is treated with more pessimism than in the case of simple geometric shapes in a low supersonic range.

After a better stabilizing surface requirement has been made, more realistic structural estimates are prepared. This leads to better center of gravity and stability estimates. Then, as a higher level of confidence is placed in the resulting trajectory analysis (velocity and altitude versus time) a specific heating analysis can be made from which still more realistic weight and balance data can be prepared. Concurrently with investigation of stability and stabilizing surface weights, it is necessary for efficient design to consider the effect on aerodynamic drag of alternative stabilizing surface shapes.

The designer is frequently faced with the dilemma of providing a sufficient magnitude of stability-producing devices, fins, or flares, to guarantee positive static stability throughout the atmospheric flight, but not so much as to yield a device sufficiently sensitive to winds as to exceed an allowable impact or test régime dispersion. This situation requires that stability margin throughout the atmospheric flight be carefully estimated and then effect of wind shears be investigated. If possible, the use of a wind tunnel investigation is recommended to better establish static stability margin, at least in that portion of the flight where the effect of wind shears is most pronounced.

Intentionally-produced low roll rates of, say, several revolutions per second, are frequently used to reduce dispersion due to 'body attached' malalignments (structural geometry or thrust). At high altitudes (no atmosphere), stability can be made to exist only by rolling to achieve gyroscopic stability. In general, roll rates required at high altitudes are higher in magnitude than the roll rates used during atmospheric flight to decrease dispersion. These rates are limited on the high side by restrictions imposed by burning motors (roll increases burning rate hence chamber pressure and case stress) or body bending stresses due to mass unbalance. The roll rates are limited on the low side by the precessional, or coning, motions allowed by the vehicle requirements. For vehicles operating out of the sensible atmosphere, roll rates of six to twelve revolutions per second are frequently encountered.

4. STRUCTURAL DESIGN AND LOADS

As a designer or design team firms up a configuration by defining the stabilizing surface requirements, it is possible to proceed with structural design. Those parameters which govern the structural design of multi-stage rocket systems include: the

basic problem, reliability, cost, quantity, structural efficiency required, time required for design, method of testing and manufacturing to be employed, desires of the customer, etc. As in any engineering problem, first one, then another of these requirements become predominant, and a continual series of compromises ultimately yields a finished design. A survey of today's flying hardware therefore looks at the results of a large number of yesterday's design conference compromises and, as one would expect, many different methods of achieving essentially the same end have been used.

The choice of manufacturing method to be employed on any part dictates profound design differences. For example, fins may be cast, molded of some sort of plastic, welded from wrought or cast raw stock, riveted from wrought, extruded, forged, or cast stock, extruded or machined from wrought bar or plate stock, etc. In the field of small rockets (say approximately $\frac{1}{2}$ ft diameter and under) produced in small quantity, much use has been made of the process of machining fins, support structure, and stage connecting hardware from bar or extruded stock. On higher production requirements, some use of the metal-to-metal gluing process has been employed. The primary reason for this difference in production method is cost differential. The 'gluing method', a cheaper method where quantity is involved, involves development effort and calendar time. The 'machining method' involves insignificant development and minimum time but is expensive in quantity.

Hardware (all parts of a rocket system exclusive of the bare motor plus nozzle) for rockets in a middle size ranging from $\frac{1}{2}$ ft to approximately 2 ft diameter necessarily requires different manufacturing techniques for quantities presently being fabricated. The difference stems from nationwide machine tool capability. Extruding two- or three-foot span fins (if practical from the structural efficiency standpoint) would not be considered today as a very practical solution, because the cost for relatively small quantities of parts would be more than the cost of a comparable fin when cast, welded, or riveted from wrought stock. As may be seen from this discussion, some clear-cut rules exist for the designer, but the solution for many problems depends upon personal preference.

In that portion of present rocket systems employing small motor sizes, the preponderance of today's systems rely upon hardware parts machined from wrought or extruded stock. Where high strengths are required, use is made of 7075 aluminum alloy plate, bar, or extruded tubes and shapes. Some parts are made of weldable aluminum, magnesium, and steels. In middle-sized portions of systems, fins are generally being welded of magnesium plate and castings, or bolted or riveted from cast and wrought materials. Some use is likewise made of aluminum alloys where better heat performance is required. In larger sized fins, single-piece aluminum or magnesium fins are being cast, wrought skins are bolted, riveted, or welded to spars which are extruded, formed, cast or forged. The choice is apparently one based upon personal preference which may be dictated by cost or fabrication means available within the designer's plant.

In the interest of describing a few specific instances, certain examples, not necessarily good ones or bad ones, will be discussed. A particular hexagonal (or modified double wedge) airfoil fin design of about $2\frac{1}{2}$ ft^2 per fin area - much used for early stage stabilization and for speeds up to Mach 6 or so - consists of identical cast magnesium leading and trailing edges welded to flat magnesium plate

sections approximately $\frac{3}{16}$ in. thick. At the area of the joint between cast and plate sections, a shear-carrying spar is welded in place. The fin assembly is then fastened to the support structure by welding. No machining of the exterior surface is attempted except to smooth up weld beads. Flats on these fins are held to within ±0.04 in.; twist, as measured by leading and trailing edges of one chord line with respect to any other chord line, is held to within ± 1/3°, and all-up weight of four fins plus mounting structure is held to about 95 lb. Where used in high temperature régimes, the leading edge is protected with stainless steel or Inconel cuffs, possibly separated from the magnesium structure by a 0.01 - 0.03 in. layer of polyester-glass cloth laminate. For very high temperature cases, the cuff is extended aft of the leading edge as necessary.

Today, a number of fin assemblies of approximately the same size and shape, but of entirely different structural characteristics, are flying successfully. One of these types is fabricated of a cast magnesium spar-rib skeleton to which are riveted magnesium skins with leading edges cuffed as necessary. Another type is fabricated of thin aluminum skin riveted to aircraft type spars and ribs, but with leading and trailing edges welded together. In both these cases the tolerances are held to much closer limits than the all-welded fin first described.

In large fin sizes (approximately 12 ft^2 in area), one planform and cross-sectional envelope has been used for a first type fabricated of a single-piece cast magnesium fin, a second type in which cast leading and trailing edges are welded to center panels, and a third type in which machined leading and trailing edges are bolted to center panels. Apparently choice between these types rests on the individuals selecting, costs, accuracy, weight, etc. Medium and large sized interstage connecting hardware has usually been manufactured from magnesium or aliminum alloy castings and machined as required. On certain configurations where hardware near the top of a stack is necessarily required to be of higher efficiency for adequate performance, the use of materials with higher allowables has dictated use of semi-monocoque design employing wrought alloys riveted or bolted.

Nose cones on vehicles of reasonably high performance have generally been fabricated of Inconel or stainless conical, ogival, or spherical weldments or spinnings. In a few cases, where necessary, specialist firms have fabricated structural shapes of ablative type materials. This technique is largely a proprietary one and as little as possible information on this design approach is made available. For specific applications some nose cones have been fabricated of beryllium, pure copper, magnesium, brass, and aluminum.

Cylindrical sections (used to provide airstream or heat protection for motor cases or payloads) have been fabricated from non-ablative polyester or epoxy glass cloth laminates, stainless steel, aluminum, etc. Weight, heat, strength, ground-handling, etc., requirements on this class of structure are very diverse, and accordingly the various solutions to the many problems are exceedingly different.

5. SEPARATION SYSTEMS

A very important class of structural components consists of the various types of separation systems. Probably the simplest, and earliest, type of separation system

used in the United States was one composed of an adapter, one end of which is bolted to the forward end of an early stage, and the other end is simply inserted into the nozzle of a latter stage (see Figure 1). This inserted portion is usually arranged with two lands, the forward land designed to insert in the nozzle throat and the aft land to engage a suitable flat provided near the exist of the nozzle. This type of joint allows differential drag to separate the stages. In the event it is desired to delay separation, a pyrotechnic fired latch may be used to prevent motion from taking place between the adapter and its nozzle.

The N.A.S.A. some years ago developed a separation system termed 'blast diaphragm' (see Figure 2). Several variations of this system subsequently were used. In general, the system consisted of (a) a female section of thread - usually 2 to 4 threads - in the exit of a nozzle, (b) the 'blast diaphragm', a slotted disc of metal, usually aluminum, whose exterior was male threaded, to match the nozzle, and (c) a female section of thread in the forward end of an adapter. In use, the adapter, blast diaphragm, and nozzle were screwed together and, as the rocket motor fired. the center of the diaphragm was blown aft by the rocket blast. In blowing aft, the outstanding legs of the diaphragm were pulled toward the center and out of engagement with the nozzle and adapter.

Marman clamps (see Figure 3) of various configurations are in present use. This type of clamp employs annular protrusions on forward and aft ends of two stages, and a series of segments designed to keep the two protrusions in contact when held circumferentially by a band. The band may then be separated at one or more places by explosively-fired bolts.

The 'shaped charge' method of cutting a joint has been used. A typical case is shown in Figure 4. A powder string encircles the missile body in the region to be cut or separated, and is surrounded on three sides by a backup ring, and on the fourth side by the missile skin. Burning action of the string or shaped charge is initiated by a blasting cap actuated by an electrical charge. When actuated, this system separates the missile skin as shown, and in so doing provides, when properly designed, a small force tending to push the separated pieces apart.

Many other less frequently used devices have been employed.

In order to provide a force to separate two sections of a rocket in those cases where an adverse drag differential exists, the following systems have been used:-

(i) Retro rocket - reverse firing rocket secured to the early stage.

(ii) Separation rocket - actually another stage and usually small in comparison with the remaining stages.

(iii) Mechanical spring - a loaded spring simply pushing at either end against the parts to be separated.

(iv) Pneumatic spring - a pressure chamber with suitable 'ends' to push against the parts to be separated and employing compressed air or other gases.

For the purpose of designing structural components one may consider two types of loading conditions - those imposed while the vehicle is on the ground, and those while in the air. Manufacturing shop and transportational handling load magnitudes are extremely difficult to define and accordingly can only be arbitrarily selected. Certain loads encountered by a vehicle while being assembled or installed on the launcher are frequently amenable to reasonable analysis. Vehicle loads encountered during launcher elevation or azimuth position changes, if applicable, may be reasonably estimated knowing launcher accelerations achievable. Wind loads exerted on the vehicle while supported on the launcher may be estimated with good accuracy. It will frequently be found that design ground loads exceed those which may be encountered in flight. One ground load always checked by many people is a 200 lb load applied vertically downward at the nose end of the missile installed on the launcher. This load was originally selected to account for the possibility of a man grabbing the missile to keep from slipping off a working stand. It is very frequently found that such a load imposes a more severe bending moment on the vehicle than any other conceivable condition.

An obvious requirement for flight loads analysis is a complete trajectory history, including dynamic pressure, spin rates, and heating input characteristics. In the event the vehicle is to be intentionally spun to stabilize or to decrease dispersion due to attached malalignments - fins, rocket nozzle, stage-to-stage, etc. - one must account not only for angle of attack, hence load due to trim conditions and wind gusts, but for loads due to spinning. If the body is appreciably elastic, aeroelasticity may need to also be accounted for. A refined analysis must also obviously take into account elasticity with all parts subjected to elevated temperature. This complete analysis is very involved and frequently portions are treated only by inspection. It will usually be found that checking for room temperature and the spinning body satisfies all but secondary requirements.

Once the flight load analysis procedure has been established, fin or body bending loads are determined, based upon (a) assumed trim conditions with gust loads superimposed (knowing reasonable or assumed malalignments and trajectory characteristics) and (b) inertial loads arising from misalignment and offset of component principal axes from the longitudinal axis. Summation of these loads may be used to prepare conventional shear and bending moment diagrams, from which a detail part stress analysis may be prepared.

After the structural loads are sufficiently well known, a detail check of stresses (on assumed member sizes) can be made. With this information at hand, stiffness parameters may be calculated. A history of body bending frequencies may now be plotted versus time and compared with aerodynamic pitching or yawing frequencies and assumed rolling rates. Should any coupling of the 'vibrational modes' appear possible, means must be taken to separate them, or, at worst, to cause the modes to cross over rapidly. In this regard attention is drawn to the fact that it is usually somewhat difficult to accurately estimate the roll-producing effect of forward canted fins on a tandem finned vehicle arrangement. For this reason possible coupling between pitching or bending and roll modes is usually treated with concern for tolerances on spin rate for those portions of the flight where spin is induced by cant of tandem fins.

6. AERODYNAMIC HEATING

The effect of aerodynamic heating on design must be considered early in design phases of a vehicle whose trajectory profile is a type resulting in such problems. Obviously, if a part is subjected to a sufficiently severe heating régime as to raise its temperature to the melting point, extreme care must be taken in design. Satisfactory flight has occurred, however, on certain fins whose leading edges actually melt. Of course, such practice is not normally followed. The usual design situation is one in which applied loads are normally calculated but, for the purpose of computing margins or factors of safety, the allowable material stress at elevated temperature is used. Data are infrequently available to substantiate strength at elevated temperature where the rate of temperature rise is even close to the rate experienced in missilry uses. Instead, one is generally forced to use steady state elevated temperature data for want of anything better. Further, a real dearth of data exists concerning materials at elevated temperature in the presence of a high velocity airstream. Conservatism in design in many instances has probably been the only reason these cases have performed satisfactorily.

Differential heating inevitably results in different expansion rates of adjacent or mating parts fabricated from different materials, or different rates even though fabricated of like materials, if the temperatures are materially different because of unlike masses, etc. Therefore, the method of fastening components together must take into consideration differential growth, else heat produced stresses are likely to fail structures designed to withstand only dynamic or aerodynamic loads.

A typical differential heating case exists in which a nose cone is secured to an afterbody by means of a ring whose design is such that the nose may carry drag loads, but may expand circumferentially (at a different rate than the afterbody due to a temperature rise difference) without failing due to thermal stress. Inspection of Figure 5 discloses a design which has been used for this sort of problem. Attention is called to the fact that the support ring is fabricated of an aluminum alloy having a higher coefficient of expansion than that of the exposed nose cone, in an effort to maintain approximately equal growth rates even though the temperatures of the parts will be different. Note also use of a laminated fiberglass 'heat shield' covered with aluminum foil to reduce the temperature of an instrument-carrying section due to radiation from the exposed nose cone.

A similar problem exists as shown in Figure 6. In this case, the mechanical design is such that, as the exterior and interior tubes grow at a different rate, motion may actually take place without affecting the functioning of the internal tube as supporting structure for the payload which is to be held at a low temperature. It will be further noted that the method of supporting payload from the inner structure is by means of relatively narrow sections which restrict heat flow (conduction) much as pressure-dropping restrictions in a hydraulic system decrease fluid flow.

Leading edge cuffs (see Figure 7) are frequently attached to adjacent fin structure by means of oversized holes in order to prevent differential expansion from providing large shear forces between bolts used to secure parts together. A similar system has been used to secure skins to stringer structure as shown in Figure 8.

7. STRUCTURAL ALIGNMENTS

In fabricating multi-stage vehicles, much stress today is being placed on designing hardware which will yield assemblies with as few malalignments as possible. Malalignments, if they exist, inevitably produce undesirable internal loads in the vehicle and flight path deviations. Interstage connecting hardware malalignments of as little as one quarter of a degree can, in the case of multi-staged devices, yield body bending moments on a spinning vehicle in excess of aerodynamic loads resulting from gusts. Fin twists of one quarter degree may likewise produce maximum root section bending moments of magnitudes approaching those resulting from aerodynamic loadings due to trim angles of attack caused by body malalignments, either stage-to-stage or fin malalignments, or gusts. As may be envisioned, vehicle trim angles resulting from body and fin malalignments in the case of a non-spinning vehicle, undesirably appear in the trajectory of such a vehicle as launcher setting errors. At high elevation launch angles, in the order of 75 to 85 degrees, where the ground angle projection of flight path deviations are high, a trim angle change from theoretical body axis of a degree or so may easily result in ground angle heading change of 5 or 6 degrees.

Satisfying a requirement for close tolerances on all surfaces exposed to the airstream commences with the selection of the method of fabrication. This selection in general precedes even the layout phase in design. It has been found possible with certain design approaches to fabricate, in production quantities, fins whose twists at room temperature are held to less than 1/10 degree. Flight test of these fins has qualitatively confirmed that, with elevation in temperature due to aerodynamic heating, no appreciable change in shape has occurred. By careful design and manufacture, it has likewise been found possible to produce a four-stage vehicle (with an overall length of approximately 50 ft) having a bow or banana shape of less than $\frac{1}{8}$ in. When this device is considered as a shaft rotating at six to eight hundred rpm, it is immediately apparent that holding bow to a minimum is very desirable in order to minimize dynamic loadings which obviously must be added to other loads existing.

8. IGNITION SYSTEMS

Every effort is generally expended in design of ignition systems to make them simple and non-ambiguous, since complexity can increase risk to life and property. The simpler a system, the easier it is understood by all likely to be concerned in assembly and checkout. Redundancy is generally provided to the greatest extent possible in order to increase the chance of a successful shot.

Dual rocket motor or separation system igniters are used wherever possible. Details of these igniters vary with the system involved. Frequently multiple squibs are used to set off the igniter charge. A multiplicity of squibs is usually wired in series parallel circuits. Igniters of the delay type may have times of from several seconds to as much as 100. A 12-second squib may have a tolerance of ±1.5 seconds, a 35-second squib, a tolerance of ±3 seconds.

If neither ground-fired nor of the delay type, igniters are frequently initiated by clockwork timers. These timers may be started by initial acceleration of the vehicle, or may be so arranged as to unlock when an umbilical wire fastened to the

launcher or other stationary object is pulled during vehicle launch. Some timers are pyrotechnically started with vehicle lift-off. Certain necessarily more complex systems may employ programming timer devices in which motor driven cams energize various circuits.

Power for ignition systems is generally provided in the form of nickel silver or cadmium batteries maintained in a dead shorted condition until all vehicle assembly is completed on the launcher and the launcher placed in the desired firing position. The batteries are then charged by means of a ground-based source via an umbilical cord which is disconnected immediately before launching.

A suitable safety device, easily accessible from outside the vehicle, is usually placed in each separate ignition circuit, permitting positive breaking of the circuit into two separate circuits until immediately before readying the vehicle for firing. This device is so arranged that in the safe position the leads from the igniter are connected together and leads from the batteries are connected together. The shorting device is placed as close as practical to the igniter. Preparation for firing then includes a continuity check of each half of the circuit and a voltage check of the battery half before connection of the igniter to the battery system. The various elements of the ignition system are connected with multiple conductor shielded wires each terminating in fittings so keyed as to preclude incorrect hookup.

9. HARDWARE FINISHES

In years past, cases arose wherein the machinist and assembler finished his work on a vehicle almost immediately prior to firing. Today, we are frequently fabricating dozens of vehicles which will be stored under extremely adverse conditions for many months. Accordingly, the problem of providing adequate storage protection for vehicles is sometimes a large one. Solutions to this problem are well known; a suitable plating of metal surfaces, adequate painting, use of strippable vinyl coatings, use of soft film corrosion preventatives, military type packaging with vapor phase inhibiting dunnage, etc.

Although this phase of the problem may seem rather prosaic, recognition of the problem, if it exists, can be every bit as important to vehicle success as recognition of any other problem.

10. LAUNCHERS

Many types of launchers are in use with multi-stage vehicles. These launchers may be 'zero length' or 'restrained' (track or tower), 'closed breech', fixed base, roadable, or moveable. In each of these types, some are designed to permit essentially unrestricted elevation or azimuth changes, while others have restricted motions. A relatively few launchers for this type of vehicle are equipped with remotely adjustable systems for controlling setting. At least one known launcher is in use wherein continuous wind information is fed into a computer, the output of which is fed into the elevation and azimuth control system to continually correct for wind dispersion until launch time. In use, certain launchers require that the missile be placed essentially vertically in the rails one stage at a time, employing a suitable crane

for hoisting. In others, the stages may be installed on the launcher, and connected to preceding stages while in a near horizontal position, with the final assembly elevated to the desired firing position. Launchers are electrically pneumatically, and hydraulically actuated.

The type of launcher to be used in conjunction with any particular vehicle may be dictated by the system requirements. For example, a small allowable dispersion may require either a track or closed breech launcher in order to have the missile traveling at relatively high speed to reduce the effect of variable ground winds. These types of launchers are more expensive to build than the zero length type and are generally used only as necessary. A high fineness ratio vehicle configuration may dictate use of a zero length launcher consisting in part of a boom which can be raised from a horizontal to a firing position. Such an arrangement permits easy assembly by stages with a support near the ends of the vehicle, thereby reducing the body bending loads. As may be seen, the launcher configuration thus must be considered during vehicle design if certain requirements are to be met. On the other hand, many vehicles have been designed around existing launchers with but small penalties being imposed upon the flying gear.

11. LOGISTICS

In order to simplify launch area assembly operations and transportation problems, an attempt is usually made to package related components (other than the rocket motors) in separate boxes. The individual boxes are frequently designed to act as work stands at the assembly site, as well as to house for shipping purposes all related parts, tools, hoisting gear, and materials such as glue, potting compounds, etc. It has been found that such a packaging procedure, in addition to being ideal from the standpoint of the assembly crew, allows the packaging engineer to completely check at the point of manufacture for items which will be required at the launching site, where missing items may be very difficult to obtain. It is of utmost importance to properly design a package support system so that usually light rocket structures will withstand often severe transportational and handling loads. Strippable plastics are frequently employed to protect surfaces from corrosion during transport and storage. Unconventionally, certain packaging can be very efficiently accomplished by completely submerging a fragile part in Vermiculite, rubberized hair, or powdered cork.

12. LAUNCHING

A well-conceived plan is usually prepared in writing in advance of moving a project to the launch area. This plan allows in the minutest detail for each operation to be performed. More than sufficient time is allowed for each step. As the assembly operations are begun all responsibilities are usually assigned to a single person. This person then in turn clearly delegates certain responsibilities to others. He then assumes responsibility for checking completion of work done against the launching plan. In this way the chance for project failure or personnel hazard is reduced to the minimum. It is considered desirable to keep to the absolute minimum the number of persons around the vehicle being assembled or placed on the launcher. By so doing fewer people are exposed to the danger of a motor prematurely igniting or exploding, and, further, the workmen are less likely to be distracted from their tasks.

After the vehicle has been completely assembled and readied on the launcher, the ignition systems are readied as previously described and the launcher aimed. The airborne batteries may then be charged, and the airborne telemetry system placed in the operating state for its last pre-flight check. Infrequently (on simple systems) a ground-based programmer has been used to mechanically perform the many battery charging and system checking functions, as well as to initiate certain functions. With all vehicle checks completed, the launch area is finally checked to see that no personnel are in the danger area, and the various instrumentation stations are checked for readiness. When all stations advise 'all clear' the vehicle is fired.

If all previous operations have been correctly completed and no omissions have occurred, the vehicle will perform successfully and the mission will be accomplished. The data may then be gathered from the many sources and subsequently reduced.

13. CONCLUSION

In reviewing the many problems associated with the design and operation of multi-stage vehicles, it will be noted that one single approach is of the utmost importance to the successful accomplishment of such a program. It is suggested that throughout the entire process the overall problem is continually reviewed utilizing the same techniques of 'preliminary design' which were used in the beginning. This 'approach', with its continually attendant look at each of the details in terms of their effect on the whole, operates in such a way as to keep any single design feature, fabrication process, or any other phase from seriously compromising the remainder of the problem.

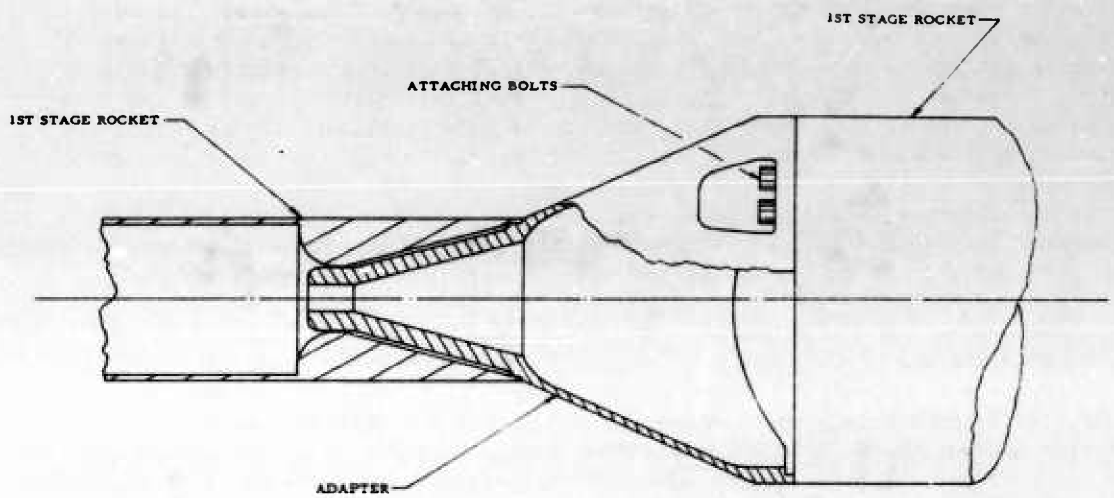

Fig. 1 Plug type adapter

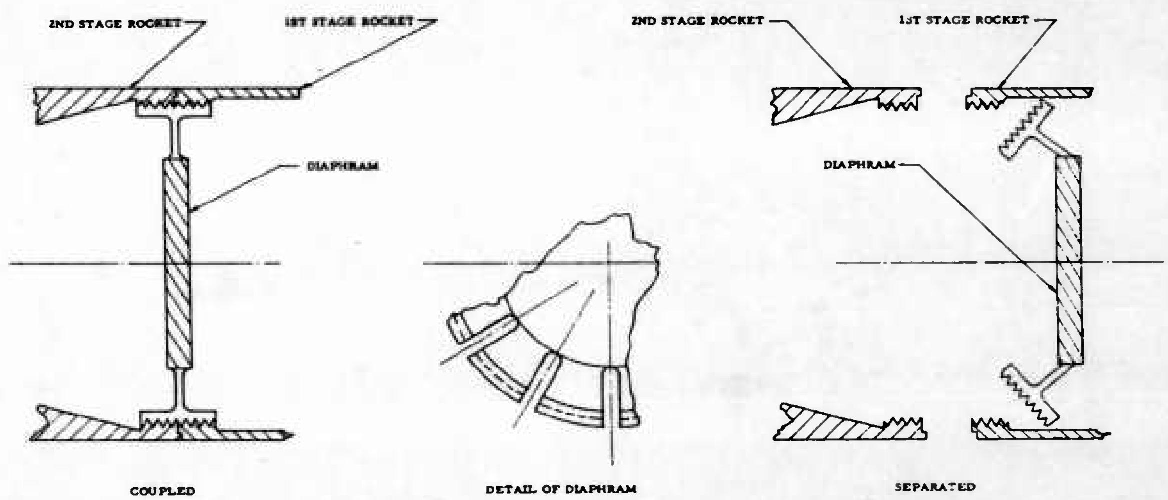

Fig. 2 Blowout diaphragm type stage-to-stage coupling

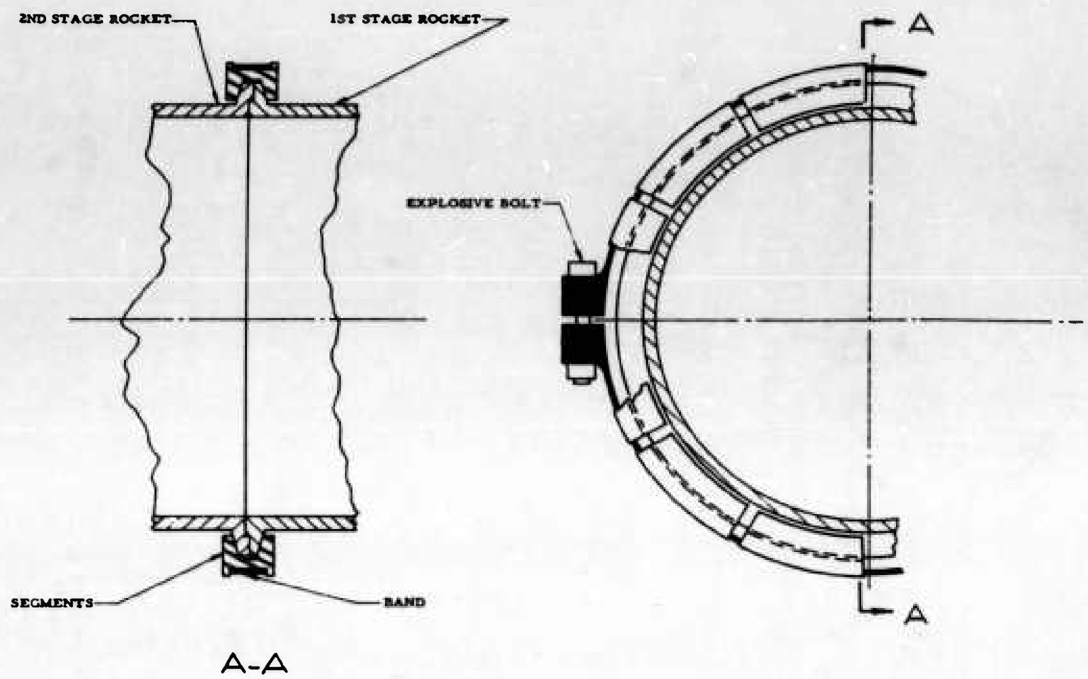

Fig.3 Marman clamp type stage-to-stage coupling

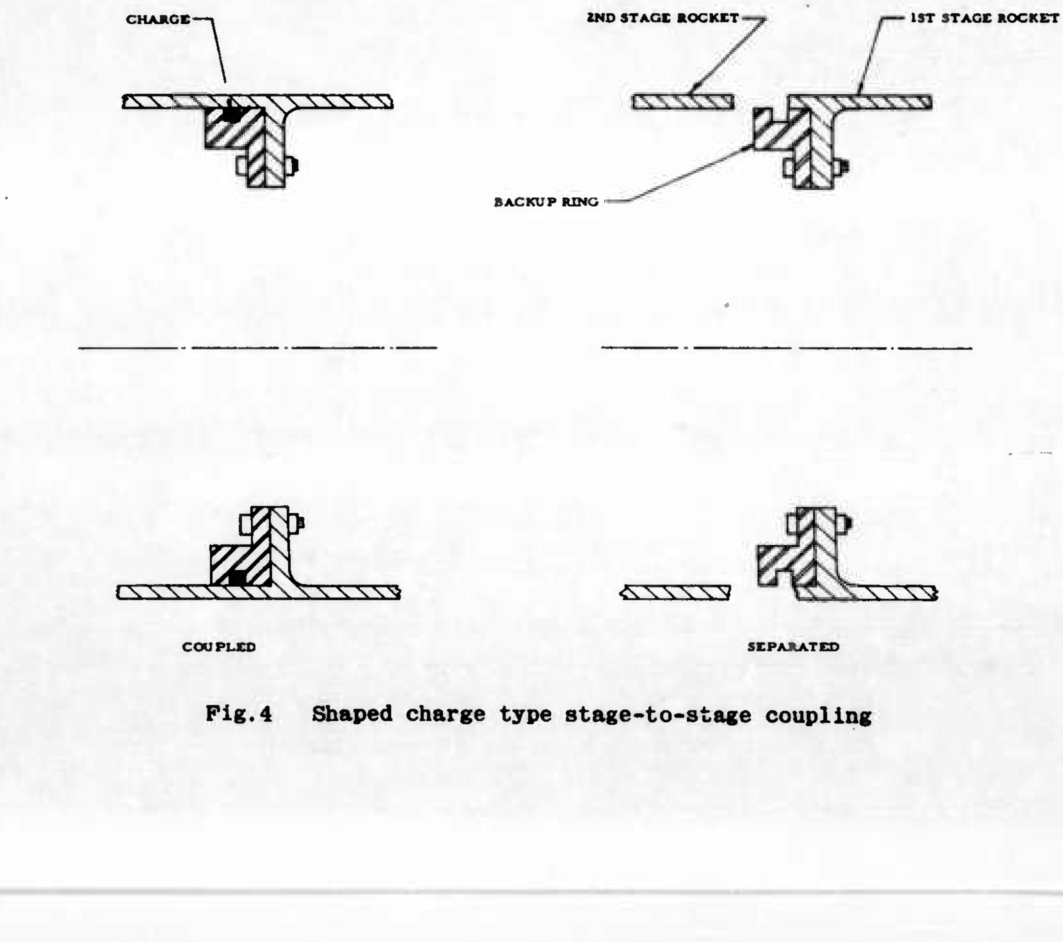

Fig.4 Shaped charge type stage-to-stage coupling

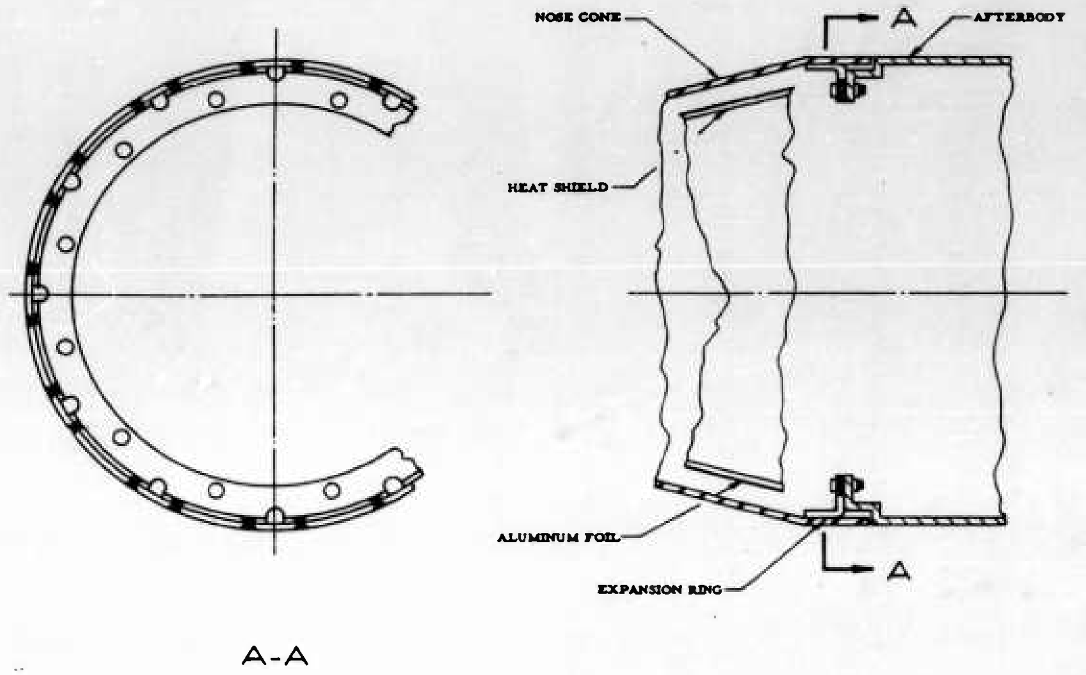

Fig.5 Method of allowing for thermal expansion

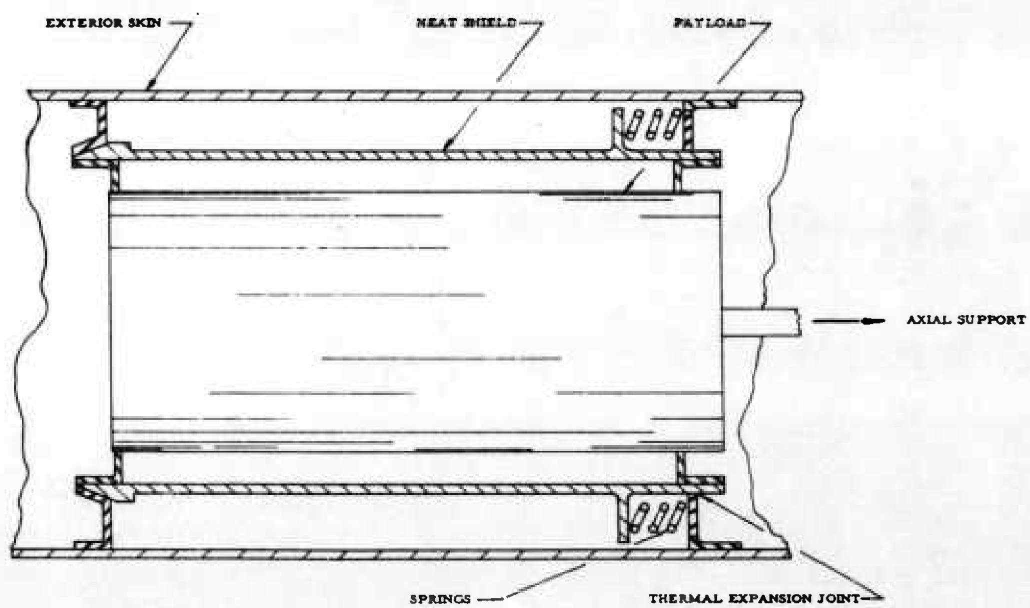

Fig.6 Method of allowing for thermal expansion

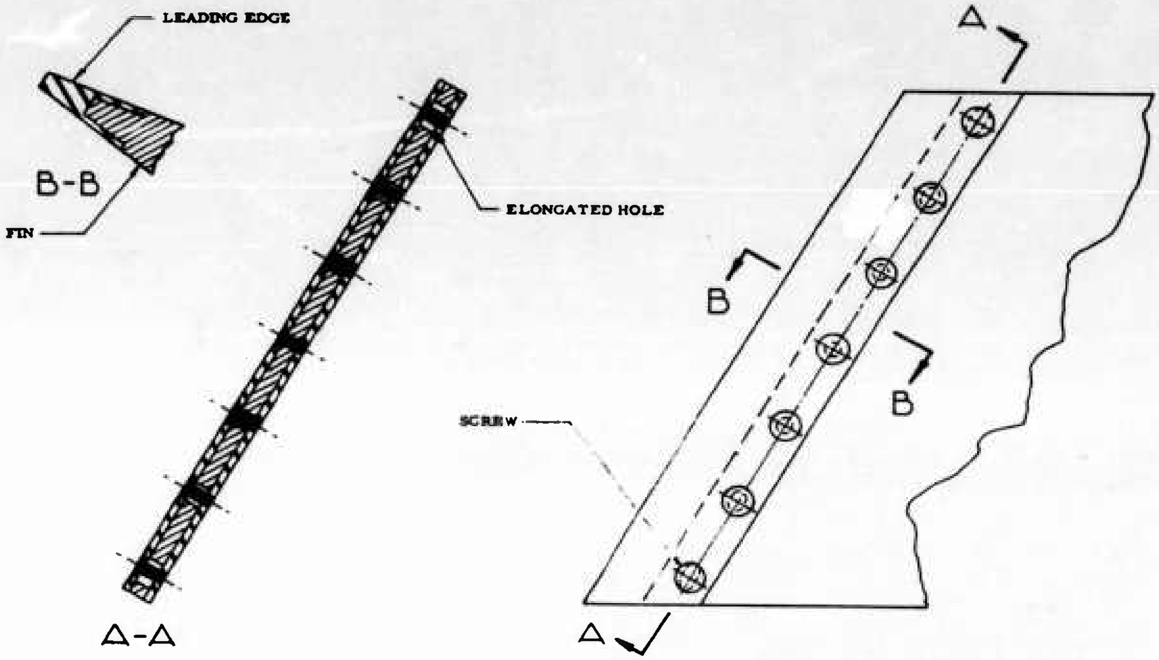

Fig.7 Method of attaching leading edge to fin for thermal expansion

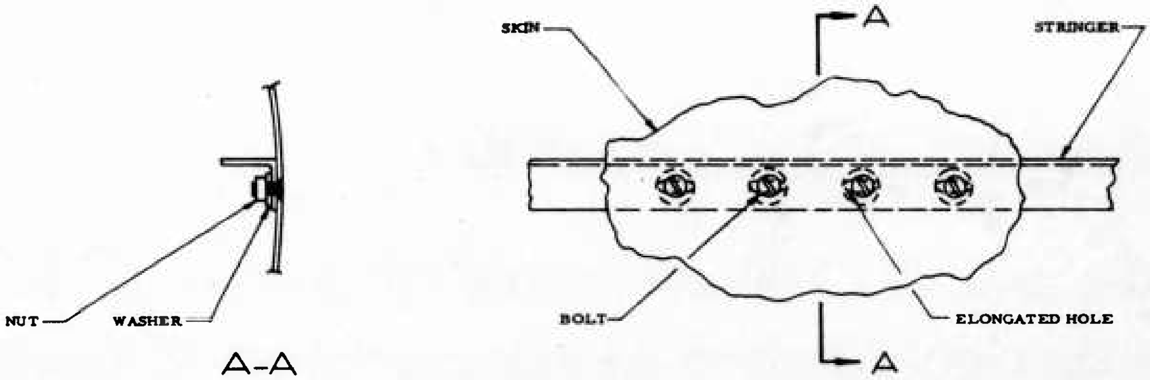

Fig.8 Method of attaching stringer for thermal expansion

DISCUSSION

J.A. Hamilton (U.K.): Could Mr. Halsted enlarge on the gust-load requirements which he uses in the design of multi-stage rocket systems?

At R.A.E. we have noted that, occasionally, appreciable bowing of rocket motors may occur owing to slight asymmetries in motor-charge burning. Has Mr. Halsted taken any account of this phenomenon in the design of vehicles which are subject to high rates of rotation?

Author's reply: For purposes of computing angle of attack due to gusts we have in general used a magnitude of 50 ft/sec for wind velocity.

This has not been taken into account, because of lack of quantitative data.

R.N.Cox (U.K.): We have heard a lot about rocket failures. What are the author's views on this: are there any common factors involved in these failures?

In this connection, to what extent do rocket designs double-up on equipment?

Author's reply: I believe that the failures to which you refer are largely associated with the more complex weapon system type rockets rather than with the type discussed during this meeting. However, as concerns failures of sounding and research type rockets, these failures today can only be attributed to oversight of the designers or people assembling the vehicles.

In general, we attempt to provide redundancy in electrical and pyrotechnical systems wherever possible. We do not usually double-up on mechanical systems.

Herr Fiebig (Germany): With regard to separating different stages of a solid propellant rocket by a blow-out diaphragm-type coupling do you have any trouble with rough burning or the like in the following stage, due to a pressure wave running into the combustion chamber?

Author's reply: In the experience of the author no difficulties of this type have been encountered.

H.I.Maxwell (U.S.): In general, no difficulties have been experienced with diaphragm separation systems in regard to causing rough burning or other motor problems. In past NASA work we have at times mounted battery packages and timers on these diaphragms. We have recently measured small amounts of 'tip-off' with these installations which we feel are attributable to protrusions into the nozzle causing flow separations in the nozzle at the moment of ignition. However, we feel that, with careful attention to detail, this is an excellent separation system.

H.P.van Leeuwnen (Netherlands): The Marman-clamp device used in stage-to-stage connection has a ring protruding from the missile surface which would cause a fair amount of drag. Do the aerodynamicists allow you to use a device like this?

Author's reply: In certain cases, notably on first to second stage joints, where drag of such a protrusion is likely to be small as compared to the thrust available, and no coasting between stages is involved, the protrusion may be tolerated in order to achieve reliability, simplicity, low cost, etc.

Anthony M.Smith (U.S.): Being primarily interested in the payload end of a rocket vehicle system, I am concerned with the performance optimization of the system. Can these systems be optimized, from a performance point of view, in a closed form type of analysis, or is one limited to strictly trial-and-error processes?

I have had occasion to examine the optimization of a down firing sequence on one rocket vehicle system, and have found this process to be amenable to a closed form type of solution. Of course this particular study was greatly simplified by the fact that most of the trajectory of interest was outside the atmosphere. But, if the rocket vehicle designer could make similar information available for the ascent trajectory, it would be of great assistance to the payload designer in helping him to make the best trade-offs for mission performance as data are acquired.

Author's reply: If one assumes, in the case of a particular group of rocket motors, that the estimated weights of structural hardware are consistent with minimum acceptable margins of safety, then the only optimization that may be achieved is by varying the coasting period between stages. In the experience of the author, trial-and-error solution of in-atmosphere coasting time optimization by means of a digital or analogue computer is the only method known which yields reasonable accuracy.

A D D E N D U M

AGARD SPECIALISTS' MEETING

ON

"THE USE OF ROCKET VEHICLES IN FLIGHT RESEARCH"

List of Papers Presented

Following is a list of the titles and authors, together with the AGARD Report number, of twenty three papers presented at the above Meeting held at Scheveningen, Holland, in July 1961.

ADVISORY GROUP FOR AERONAUTICAL RESEARCH AND DEVELOPMENT
Organisation du Traité de l'Atlantique Nord
64, rue de Varenne - Paris 7ème

June 1962

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This Report is one in the Series 375-397, inclusive, presenting papers, with discussions, given at the AGARD Specialists' Meeting on 'The Use of Rocket Vehicles in Flight Research' at the Kurhaus Hotel, Scheveningen, Holland, 18-21 July 1961, sponsored by the AGARD Fluid Dynamics Panel.

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1961
17 pages, incl. 8 figs; plus discussion and bibliography of papers presented at the 'Use of Rocket Vehicles in Flight Research' Meeting

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P.T.O.

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